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COMBINATIONS OF STRAIN AND PENDULUM SEISMOGRAPHS TO ENHANCE LONG PERIOD P AND RAYLEIGH WAVES AT QUEEN CREEK, ARIZONA

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The long-period pendulum instruments at QCAZ are used as a standard for comparison. Outputs of the strain and pendulum seismographs are combined using an analog computer. The resultant output is then compared for a sample of forty-four earthquakes to the appropriate pendulum to establish signal-to-noise ratio gain (or loss). Visual inspection of the data samples verifies that cancellation of sixteen second microseisms occur. The lack of reduction of the rms noise amplitude is principally a result of strain system noise at periods greater than 16 seconds.

Effective Rayleigh wave signal enhancement can be obtained either with the vertical or horizontal system. P wave signal enhancement can be obtained using a horizontal strain-pendulum pair. In both cases the gain is about 5.5 db as compared with a maximum possible gain of 6 db.

However, when the signal-to-noise ratio gain (or loss) for P waves is determined, the result is an average net loss. This amounts to 0.9 to 6.8 db, depending on the instrument combination being analyzed. The beam signal-to-noise ratio improvement for Rayleigh waves varies from a gain of 4.2 db to a loss of 2.1 db.

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INTRODUCTION

The Queen Creek strain seismograph installation includes both strain and pendulum instrumentation with response from about 5 Hz to about 600 seconds. The installation is described by Fix and Sherwin (1970). Many aspects of the data could be analyzed, however this report is limited to the analysis of long-period P waves and Rayleigh wave signals as recorded on the system whose peak response is about 25 seconds. Analog techniques are used.

A large number (150 to 200) of earthquakes were examined to see how well they were recorded at QCAZ. Forty-four were selected for some analysis. The NOS data for the selected events is included as Appendix I. The earthquakes are assigned numbers for ease of reference. Figure 1 is a map showing their location.

Theoretical background

Benioff (1935), Benioff and Gutenburg (1952), Benioff (1962), and Romney (1964) described the application of combinations of strain and pendulum seismographs to enhance body and surface waves in the presence of noise.

Romney (1964) is the principal reference for enhancement of P waves using the sum (or difference) of properly matched strain and pendulum seismographs. For teleseismic distances a vertical strain seismograph is more insensitive to P waves than a vertical pendulum when the

instruments are matched for Rayleigh waves. Thus for a site where the noise consists predominantly of a single Rayleigh mode, it should be possible to cancel the noise and leave the P wave signal on the pendulum intact. Romney also showed that

$$\frac{\partial \mu}{\partial x} \times \frac{\partial v}{\partial y} = - \frac{\lambda + 2\mu}{2} \frac{\partial w}{\partial z}$$

where the partial derivatives are the orthogonal components of strain and λ and μ are Lamé constants. The formula is derived for the free surface of a homogeneous isotropic half-space. This formula allows the substitution of the sum of an orthogonal horizontal pair of strain seismographs for the vertical strain seismograph, to cancel Rayleigh wave noise. Both methods are used in this analysis.

The response of matched horizontal strain and pendulum instruments with electromagnetic transducers to earthquake generated P and Rayleigh waves is:

$$\frac{\text{Horizontal Strain}}{\text{Horizontal Pendulum}} = - \frac{1}{C_p}$$

for P waves, and

$$\frac{\text{Horizontal Strain}}{\text{Horizontal Pendulum}} = \frac{\lambda}{\lambda+2\mu} \frac{1}{C_R}$$

for Rayleigh waves,
where C_P and C_R are the corresponding phase velocities and the formulas have been derived for a homogeneous isotropic half space. Analysis of the data shows that these formulas are adequate to serve as a guide to setting relative gains of the seismographs as inputs to the computer. In each case it was possible to experimentally set the gains to enhance the wave type being analyzed. The beam response is discussed by Benioff (1962). When the gains are adjusted for P waves, Rayleigh wave noise cancellation is incomplete by a factor which depends on the phase velocity, which in turn depends on the epicentral distance. When the gains are adjusted for Rayleigh waves, Rayleigh wave noise whose azimuth is outside the beam is partially cancelled. Woolson (1971) discusses the comparative response between the horizontal strain/pendulum beam at QCAZ to the horizontal long-period array at TFO (Tonto Forest Observatory).

Analysis procedure

Analog procedures have been employed to facilitate the analysis of a large number of events. The following steps occur in the analog analysis:

1. Select events whose azimuth falls with the 60° beams in the four directions from QCAZ centered along 55°, 145°, 235° and 325° (the installed azimuths of the horizontal instruments).

2. Check the films or make an analog playout of the tape to verify signals at QCAZ at a useable level.

3. Measure the peak amplitude of the sum and difference of the horizontal strain and pendulum records after they have been normalized by setting the peak Rayleigh wave signals to be equal on both channels. After normalization, measure the rms noise and signal amplitudes, the calibrations, and the rms amplitudes of the calibrations.

4. For those events where some evidence of a long-period P wave exists, repeat step 3, except that gains are normalized to the P wave signal rather than the Rayleigh wave signal.

5. For the events analyzed above, measure the sum and difference of the 90° phase-shifted vertical strain and pendulum, normalizing the gains at the Rayleigh wave signal. After normalization, measure the rms noise and signal amplitude, the calibrations, and the rms amplitude of the calibrations.

6. Repeat step 5, except that the sum of horizontal strains is substituted for the vertical strain. (The contribution of each horizontal instrument to the sum is set from their respective calibrations.)

(The 90° phase shift circuit used is centered at

at about 20 seconds period. Tests of the circuit showed no discernible discrepancy at 20 seconds period. At seven seconds period the phase shift is off about 20°.)

The high level of noise on the strain seismograms made it desirable to prefilter the data in order to properly set the gains. This also avoided the problem of loading the rms amplitude circuits, which are leaky integrators, with high amplitude non-seismic noise. A final stage of filtering was used to attenuate seven-second microseisms, which in some cases were not properly cancelled by the strain-pendulum combinations. Figure 2 illustrates the effects on the advanced long-period response of the 0.05 and 0.025 Hz 24 db/octave high-pass filters and the final 0.1 Hz low-pass filter. Digital analysis of "quiet" samples of strain and pendulum noise shows that there is commonly about 35 db difference at 40 seconds period between the strain and pendulum seismographs. It is this 35 db of excess noise on the strain seismograph that the high pass filter is designed to attenuate. The 0.1 Hz low-pass filter is applied to outputs after the phase shifts, sums and differences, have been written.

Numbers in parenthesis (-) refer to the list of earthquakes in Appendix I. Analysis consists of examining some particular aspect of the seismogram for a selected subset of these earthquakes.

RESULTS OF ANALYSIS

Long-period P waves - horizontal instruments

Table I summarizes the results obtained for the nine earthquakes for which some evidence of a long-period P wave was found. The average magnitude is 5.5 (m_b from NOS), the extremes are 6.6 and 5.1.

The first group of columns contains the results for long-period horizontal strain and pendulum combinations. As previously noted, Benioff (1962) showed that a horizontal strain and pendulum seismograph could be summed to enhance P or SV waves. If the horizontal strain and horizontal pendulum are in phase and equal in amplitude for P waves, then the ratio of amplitude sum (or difference) to the vertical pendulum should be 6.0 db. The average value obtained for the ratio was 5.5 db. Amplitudes were arbitrarily adjusted to make them equal, however no control of phase was made.

The noise amplitude is defined as the rms amplitude of the noise prior to the observed signal. Analog circuitry is used to obtain a smoothed value of the noise. The time constant of the smoothing circuit is 40 seconds, about two cycles at the peak response of the system. The signal amplitude is the peak-to-peak amplitude. Signal-to-noise ratio is defined as (peak-to-peak)/rms amplitude.

Figure 3 shows that the horizontal strain and pendulum seismographs are in phase for the P wave signal from an earthquake (m_b = 6.6) from the Sea of Okhotsk (48),

TABLE IA

Signal Gain - Signal/Noise Ratio Long Period P-Waves

Earthquake	Signal Sum or Difference over Horizontal Pendulum 55° Ratio	55° db†	325° Ratio	325° db†	Horizontal Pendulum (p-p)/rms Ratio	Horizontal Pendulum (p-p)/rms db†	Sum Horizontal Pendulum Horizontal Strain (P-P)/rms Ratio	Sum Horizontal Pendulum Horizontal Strain (P-P)/rms db†	db†
3			6/3	+6	3/1	+9.6	6/1	+15.6	+6.0
6	19/11.5	4.4			11.5/2	+15.2	19/6	+10.0	-5.2
21			32.5/.7	+5.6	17/1	+24.6	32.5/4	+18.2	-6.4
17	37/21.5			+4.7	21.5/4	+14.6	37/10	+11.4	-3.2
37	17/8			+6.6	8/2.5	+10.1	17/10	+ 4.6	-5.5
8	Not Identifiable								
42	13/9			+3.2	9/1	+19.1	13/1	+22.3	+3.2
45	32/16			+6.0	16/2	+18.1	32/3	+20.6	+2.5
48	27/11			+7.8	11/1	+20.8	27/2	+22.6	+1.8
			Average	+5.5				Average	-0.85

† (+) db Gain
(-) db Loss

TABLE IB

Signal Gain - Signal/Noise Ratio Long Period P-Waves

	PZL (P-P)/rms		SZL ± PZL (P-P)/rms			With 0.1 Hz lowpass output filter	
Earthquake	Ratio	db†	Ratio	db†	db†	* Ratio	* db†
3	8/1.5	14.6	10/1.5	16.5	+1.9		
6	7/1.5	15.4	7/4	4.8	-10.6	7/2	-4.5
21	19.5/1.0	25.8	19.5/15	2.3	-23.5		
17	23/2.5	19.1	23/3	17.7	- 1.4		
37	18/2.5	17.2	19/8	7.5	- 9.7		
8	16/2	18.1	18/2	19.1	+ 1.0		
42							
45							
48	21/1	26.4	21/1.5	20.9	- 5.5		
				Average	- 6.8		
					- 4.1 with Earthquake 21 eliminated		

†(+) db Gain
(-) db Loss

*Net gain or loss with 0.1 Hz low pass filter

TABLE IC

Signal Gain - Signal/Noise Ratio Long Period P-Waves

	PZL		(S55L+S325L)±PZL				
Earthquake	(P-P)/rms Ratio	db†	(P-P)/rms Ratio	* db†	* db†	Net	Notes
3	3/1	9.6	10/1	20.0	+10.4		Large signal gain sum horizontal strains indicates system noise is being called signal.
6	10/1.5	16.9	11/4	8.8	-8.1	10/1.5 0.0	
21	15/1	23.5	22.5/4	15.0	-8.5		
17	27/2.5	20.7	25.5/4	16.1	-4.6	23.5/25-1.3	Lowpass filter on SZL ± PZL has maximum 21.0 db, minimum 13.1 db, thus gain of 1.9 db or loss 6.0 d
37	7/1	16.9	13/4	10.2	-6.7		
8	11/1.5	17.3	11/3	11.3	-6.0		
42	36/2	25.1	33/1.5	26.8	+1.7		
45							
48				Average	-3.1 **		

†(+) db Gain
(-) db Loss

*Net gain or loss with 0.1 Hz low pass filter

**Average -5.4 db when Earthquake (3) is not used.

P, PcP and PP are well-recorded. There is also some evidence that PPP is better defined on the difference trace. In this case the difference is a northeast beam. Data for this earthquake (48) are listed in Table I. Only the horizontal instruments are illustrated in Figure 3. For a P wave it is not possible to predict a theoretical signal-to-noise gain for the sum (or difference) of the horizontal strain and pendulum over the single pendulum instrument. When the gains are set to enhance P waves they will not necessarily be set to cancel or enhance Rayleigh wave noise. Cancellation can at best be only partial. This phenomena is illustrated by the seismograph of a long-period P wave from the Kermadec Islands (37). Figure 4 is the horizontal southwest beam. The P wave is marked. It is not well-defined and probably would not be recognized from this information alone (in Figure 9 the signal is clear on the vertical pendulum record). The seven-second microseisms are enhanced on the sum (the southwest beam). Figure 5 is the same data with the gains reset to cancel the seven-second microseisms on the difference trace, which is a northeast beam. For this time period, and rather commonly, the seven-second microseisms are predominantly from the southwest.

The signal-to-noise ratio gain (or loss) for long period P on the horizontal instruments is listed in column 2 of Table I. As mentioned at the end of the previous section one should not attach much significance to the numbers since they principally reflect instrument noise levels. Evidently the system noise overwhelms any contribution from the beam.

Long period P waves - vertical instruments

As described by Romney (1964), it should be possible to use combinations of strain and pendulum seismographs to cancel Rayleigh wave noise. In this case the vertical strain (or equivalent sum of horizontal strain) seismograph is relatively insensitive to teleseismic P waves. P wave enhancement results from an undisturbed P wave and cancelled Rayleigh waves on the phase-shifted sum or difference. The analog circuitry used in this analysis produces a pair of outputs 90° out of phase, from a single input. The phase shift relative to the original record is approximately a linear function of frequency. The pair of channels (one strain and one pendulum) used to determine cancellation is selected from the two pairs of outputs. The symbol (PZL)° seen in Figure 6, for example, is used to indicate this phase shift and selection process, prior to determining the sum and difference.

The results of using the vertical strain or sum of horizontal strain seismographs to cancel Rayleigh wave noise is summarized in column 3 of Table I. For seven earthquakes using the vertical strain to cancel noise, the average signal-to-noise ratio loss is 6.8 db. Using the sum of the horizontal strain seismographs to produce an equivalent vertical strain, the signal-to-noise ratio loss is 3.1 db, as seen in column 4. The vertical pendulum is used as the standard for comparison. Visual inspection of many seismograms shows that non-seismic noise on the strain instruments is the cause of the loss. Digital analysis of QCAZ data (Woolson 1972)

shows that a linear combination of either the vertical strain and vertical pendulum or the sum of the horizontal strains and the vertical pendulum seismographs can be used to cancel the seven-second microseisms. The amount of noise reduction obtained is 8 to 10 db. For the 16-second microseisms, it is shown that the combination of the sum of the horizontal strains and the vertical pendulum is more effective in some cases. The numbers are 0 - 5 db for the vertical and 0 to 10 db for the horizontal strain seismographs. Outside the 7- and 16-second microseismic bands no cancellation can be expected. At 30 second periods the loss can be as much as 20 to 30 db. All data available show that there exists noise (presumably nonseismic) on the strain seismographs whose period is greater that about 20 seconds, and which does not occur on the pendulum seismographs. This noise cannot be cancelled on any strain-pendulum combination. The result is a signal-to-noise ratio loss when the combination is compared to the vertical pendulum instrument.

Figure 6 shows the result of analog analysis of the vertical instruments for an Okhotsk earthquake (48) used to illustrate the horizontal beam for P waves (Figure 3). In this case the sum of horizontal strain seismographs is used in place of the vertical strain. Gains are set to cancel Rayleigh waves using the Rayleigh wave signal from the earthquake (not illustrated). The contribution of each of the horizontal instruments to the sum is controlled by their respective calibrations. As expected, there is no P wave signal on the equivalent vertical

strain. There is limited evidence of enhancement of the seven-second microseisms on the sum and cancellation on the difference. There is apparent excess noise on the sum of the horizontal strains that occurs on both the sum and the difference. Figure 7 is an example of cancellation of sixteen-second microseisms prior to an earthquake from the Tonga region (8). The bursts of non-seismic noise enclosed in dashed lines are not used in any of the rms amplitude calculations. The sixteen-second microseisms on the sum and not on the difference at 1045, 1052:30 and 1055 are examples of cancellation. The rms amplitude to determine signal-to-noise ratio loss was measured between 1045 and 1050. Figure 8 is the same data as Figure 7, except that the vertical strain seismograph is used with the vertical pendulum in an effort to cancel noise. No apparent noise cancellation occurs.

Figure 9 shows good cancellation of the seven-second microseisms in spite of severe 20 to 25 second noise on the vertical strain seismograph that contaminates the sum, causing a loss in signal-to-noise ratio as compared with vertical pendulum. The measured loss is 9.7 db. The earthquake occurred in the Kermadec Islands region on 10 November 1970 (37). It is customary to set gains on the vertical strain and pendulum seismographs equal for the Rayleigh wave signal from an earthquake. This usually is a well-defined part of the signal. The presence of a Rayleigh wave signal is also used as a measure of whether or not an earthquake was recorded at QCAZ. The sum and difference of the phase-shifted inputs

is a measure of how well the system is working to cancel Rayleigh waves. Rayleigh wave noise with the same phase velocity and mode as the signal Rayleigh wave should be cancelled the same amount. This turns out to be an average of about 12 db, or 4 to 1. It is likely that about this much Rayleigh wave noise is cancelled, as shown by isolated segments of data (Figures 7 and 9). That this much cancellation of noise (Rayleigh plus non-seismic noise) does not occur on most seismogram combinations is due to a low ratio of Rayleigh wave noise to non-seismic noise. Tables II and III summarize these data for the events. Table II is the signal cancellation using the vertical strain and pendulum. In Table III the sum of the horizontal strains replaces the vertical strain.

Long-period Rayleigh wave earthquake signals

Earthquakes were selected for this analysis on the basis of the Rayleigh wave part of the signal as recorded at QCAZ. We used only those events whose back azimuth at QCAZ falls within the 60 degree beams centered at the installed azimuths of the horizontal strain and pendulum seismographs. Events which occurrred during times of high noise level, or for some other reason did not have a well-defined Rayleigh wave signal at QCAZ, were eliminated from the sample. It is estimated that of the events examined, about 25% - 30% have been used in the analysis.

The back azimuth cancellation is listed in Appendix I. This is the amplitude of the ratio of the sum to the

TABLE II

Rayleigh Wave Cancellation Vertical
Strain/Vertical Pendulum

Earthquake	Peak-Peak Ratio	Peak-Peak Ratio	rms Amplitude Ratio	rms Amplitude Ratio (db)
14	38/10	11.6 db	14/4	10.9 db
15	50/7.5	16.5 db	16/5	10.1 db
13	50/13	11.7 db	19/6	10.0 db
7	47/10	13.4 db	14/4	10.9 db
19	50/12	12.4 db	17/5	10.6 db
21	37/9	12.3	20/5	12.0 db
17	52/8	16.2	17/4	12.6
1	46/10	13.2	15/4	11.5
26	55/16	10.7	NOT RUN	
28	15/3	14.0	NOT RUN	
		Average 13.2 db		Average 11.8 db

(SZL - PZL)/(SZL + PZL)

Rayleigh Wave Signal Cancellation

TABLE III

Rayleigh Wave Rejection - Independent of Azimuth

Earthquake	Peak-Peak DIFF/SUM	db	rms DIFF/SUM	db	
31	55/18	9.7	23/5	13.2	
36	50/11	13.2	17/5	10.6	
27					
37	50/12	12.4	13/2	16.2	
38	43/10	12.7	13/6	6.7	Noisy
39	33/10	10.4	10/2.5	12.0	
40	41/13	10.0	12/5	7.6	
41	49/13	11.5	13/4	10.2	
42	48/11	12.8	15/4	11.4	
19	50/8	15.9	17/2	18.6	
43	27/7	11.7	9/3	9.6	
		Average 11.9 db		Average 11.6	

[(S55L + S325L) - PZL]/[(S55L + S325L) + PZL]

difference for horizontal instruments. Measurement is made at the approximate twenty-second peak in the Rayleigh wave signal. The numbers are a function of magnitude, distance, noise, and Rayleigh wave signals from the opposite azimuth. The principal use of the data is to verify that the system can be set to cancel Rayleigh wave noise. The assumption is that the noise is the same mode and has the same phase velocity as the earthquake signal. It is generally possible to tune the instruments to cancel any segment of Rayleigh wave noise, providing it is undirectional, consists of a single mode, and occurs within the 60° beam of the four available directions.

Data for the amplitude sum or difference of the horizontal instruments over the amplitude of the horizontal pendulum are listed in Table IV. This gain should be very nearly 6.0 db. The prefiltering is such that the signal is dominated by the twenty-second Rayleigh wave, which is commonly the highest amplitude part of the signal when the bandwidth of the system is decreased. The data can be summarized as follows:

Direction	Ratio	Number of Earthquakes	Average Signal Gain
Northeast	(S55L-P55L)/P55L	7	5.4 db
Southeast	(S325L-P325L)/P325L	16	4.9 db
Southwest	(S55L-P55L)/P55L	12	6.1 db
Northwest	(325L-P325L)/P325L	5	4.5 db

TABLE IV

Gain of Sum or Difference over Horizontal
Pendulum for Rayleigh Waves

Earthquake	System	(P-P)	db	rms	dh	
4	325	37/22	4.1	12/7	4.7	
1	325	15/10	3.5	5.5/4	2.8	
2	325	36/24	3.5	14/7.5	5.4	
7	325	40.5/31.5	2.2	13/10	2.3	
8	55	52/23	7.0	18/8.5	6.5	
10	55	9/5	5.1	4/2	6.0	
12	55	50/25	6.0	17/7.5	7.1	
13	325	29.5/14	6.5	19/9	6.5	
14	325	66/35	5.5	21/11	5.6	
15	55	60/19	10.0	19/9	6.5	
18	55	32/18	5.0	10/5	6.0	
19	325	26/11	7.9	9/5	5.1	
16	55	40/30	2.5	17/10	4.6	High level of 7 sec microseisms causes confusion
16	55	44/36	1.8	15/9	4.4	
20	325	28/17	4.3	9/5	5.1	
21	325	55/30	5.2	20/10	6.0	
17	55	60/35	4.6	19/10	5.6	
22	55	52/25	6.3	18/8	7.0	
23	325	60/36	4.4	22/12	5.2	
24	325	53/29	5.2	21/12	4.8	
25	325	44/32	2.8	23/10	7.2	
11	55	47/24	5.8	17/8	6.5	
26	325	39/20	5.8	NOT RUN		
27	55	28/12	7.4	7/4	4.8	
28	55	25/12	6.4	NOT RUN		
29	325	20/11	5.2	NOT RUN		
30	325	19/12	4.0	NOT RUN		
31	325	50/29	4.7	10/5	6 db	
32	55	37/19	5.8	NOT RUN		
33	55	30/15	6.0	NOT RUN		
34	55	48/20	7.6	NOT RUN		
35	55	NOT USABLE				
36	325	53/28	5.5	22/11	6 db	
37	55	55/28	5.9	20/10	6 db	
38	325	37/24	3.8	14/9	3.8	NOISY
39	55	34/17	6.0	6.5/4	4.2	
40	325	55/26	6.5	17/9	5.5	
41	325	57/31	5.3	17/8	6.6	
42	325	50/20	8.0	17/9	5.5	
43	325	34/23	3.4	11/7	3.9	
44	325	14/9	3.8	4/2	6.0	
45	Clipped					
46	55	19/10	5.6	6/4.5	3.5	
47	55	55/26	6.5	18/9	6.0	
48	Clipped					

The signal-to-noise ratio gain (or less) of the sum or difference of the horizontal strain and pendulum seismographs over the signal-to-noise ratio of the horizontal pendulum is listed in Table V. The average for 31 earthquakes is 1.7 db improvement. The sum or difference should cancel noise outside the beam. This is about five-sixths of the noise amplitude using a 60 degree beam width. There is a signal gain of 6 db. One can thus expect as much as 21.6 db under these assumptions. This assumes that the noise is random in direction at QCAZ; an assumption that does not fit the dominant direction known for both 7- and 16-second microseisms, (southwest for the seven-second and northeast for the sixteen-second microseisms). If all the noise is Rayleigh wave noise with the same phase velocity and mode as the signal and has its azimuth within the beam, then no signal-to-noise gain can be expected. There is thus wide variation in the expected value. Of the 31 earthquakes analyzed 8 have a gain greater than 5 db.

Figure 10 is an example of simultaneously occurring Rayleigh wave signals from opposite azimuths. One earthquake occurred in Albania (10) and the other in the Solomon Islands (9). The signal from Albania is enhanced on the difference and the signal from the Solomons is enhanced on the sum of the horizontal strain and pendulum.

In order to further measure noise cancellation ahead of the signal, a limited sample using the sum of the horizontal strain seismographs for the vertical

TABLE V

Rayleigh Wave Signal/Noise Data

Earthquake	Sum or Difference	Horizontal Pendulum	Gain (+) Loss (-)
2	27.8 db	23.7	+4.1
7	20.1	24.0	-3.9
8	34.3	34.0	+0.3
12	34.0	21.8	+12.2
13	27.3	23.4	+3.9
14	24.3	24.2	+0.1
15	35.6	30.1	+5.5
18	18.0	17.2	+0.8
19	14.0	17.5	-3.5
16	10.0	10.5	-0.5
20	26.2	29.2	-3.0
21	35.6	29.5	+6.1
17	36.5	30.4	+6.1
22	31.0	28.0	+3.0
23	20.0	21.4	-1.4
24	26.0	38.3	-12.3
25	23.5	24.1	-0.6
11	23.9	18.4	+5.5
27	21.0	14.0	+7.0
31	24.4	23.2	+0.8
36	25.2	30.4	-5.2
37	25.2	23.5	+1.7
38	19.3	17.7	+1.6
39	22.4	21.0	+1.4
40	25.2	22.6	+2.6
41	17.9	17.0	+0.9
42	34.0	26.0	+8.0
43	24.6	20.8	+3.8
44	10.9	14.8	-3.9
46	24.6	20.0	+4.6
47	34.8	28.3	+6.5

Average +1.7

strain with the vertical pendulum has been analyzed. These data show an average loss of 2.9 db (Table VI.)

TABLE VI

Cancellation of Noise Prior to Signal
(Sum of Horizontal Strains for Vertical Strain)

Earthquake	Difference/PZL
42	0 db
38	-5.1 db
40	0 db
39	-3.5 db
37	-2.5 db
36	-6.0
43	-3.0

CONCLUSIONS AND SUMMARY

The analog analysis of long-period P waves and Rayleigh waves from earthquakes demonstrates that combinations of strain and pendulum can be used to enhance signals and cancel noise in the 7- to 23-second band at the QCAZ (Queen Creek, Arizona) strain seismograph installation. The instrument response to P waves and Rayleigh waves conforms to that theoretically predicted.

Application is limited by apparent non-seismic noise on the strain seismographs. This noise commonly results in a signal-to-noise ratio loss on the combined instruments as compared with the appropriate pendulum seismograph.

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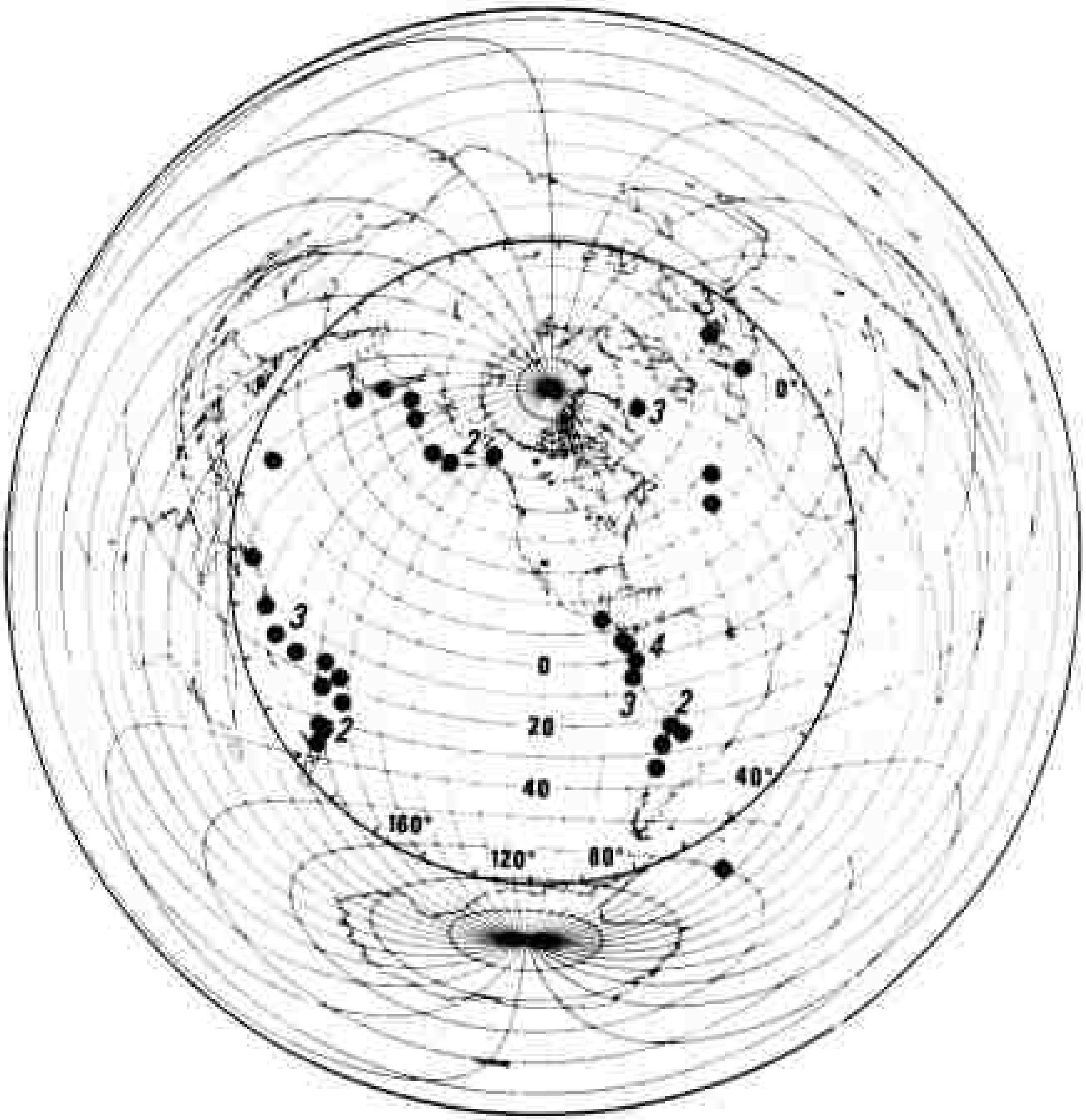


Figure 1. Epicenters of earthquakes used in analysis.

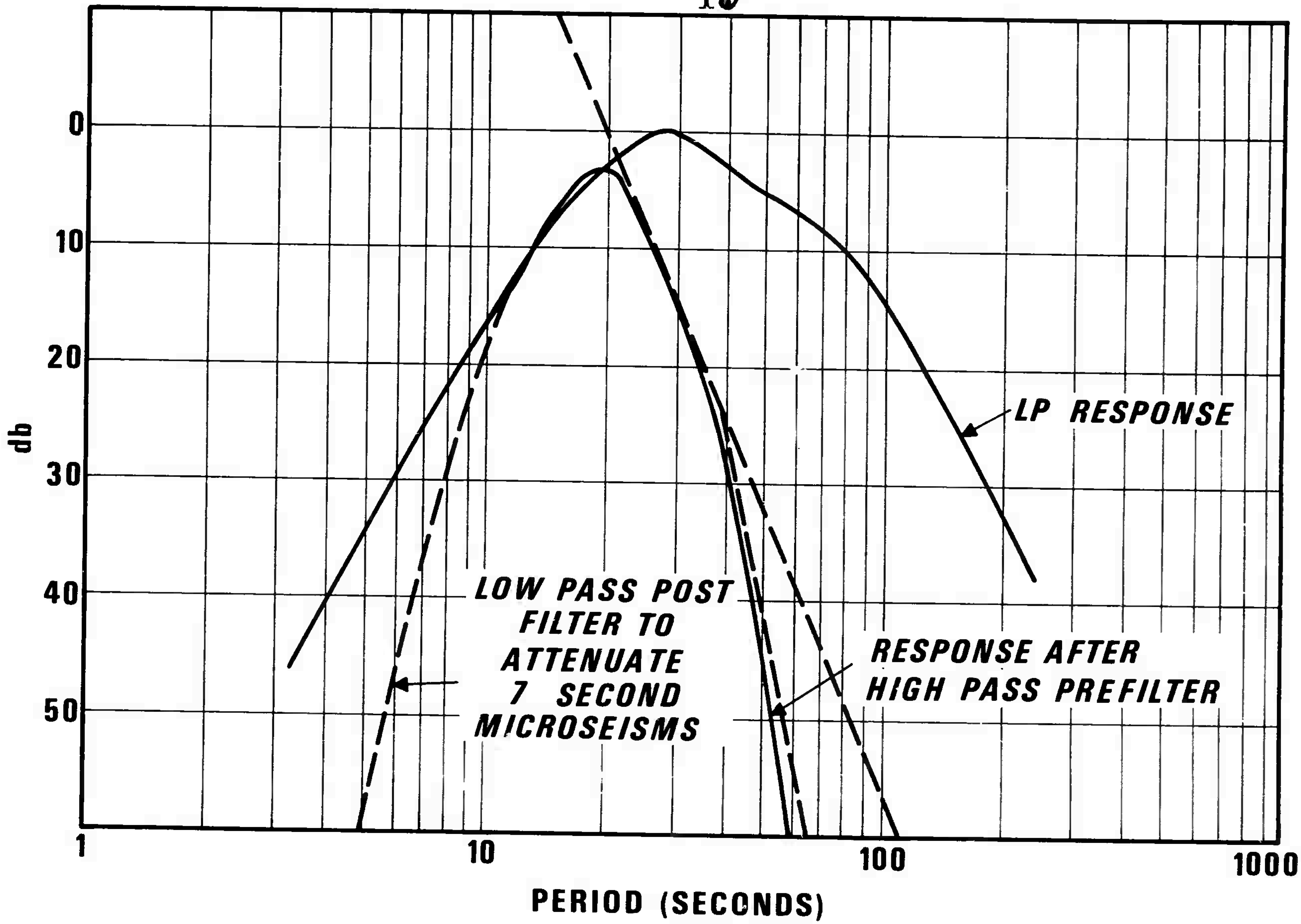
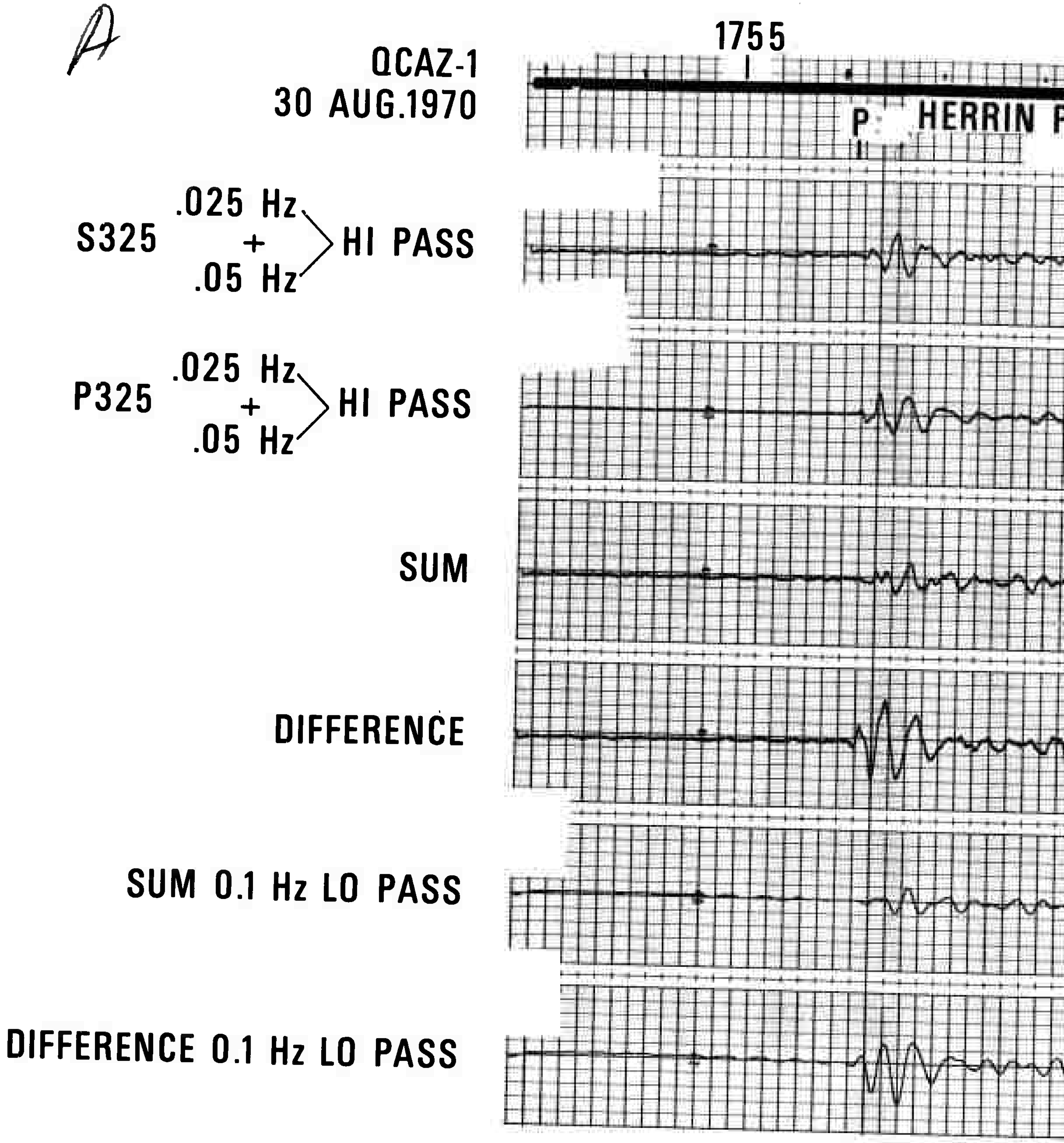


Figure 2. Filtered long period response.

A


1755
QCAZ-1
30 AUG.1970
P
HERRIN F
S325
.025 Hz
+
.05 Hz
HI PASS
P325
.025 Hz
+
.05 Hz
HI PASS
SUM
DIFFERENCE
SUM 0.1 Hz LO PASS
DIFFERENCE 0.1 Hz LO PASS

Fi
ea

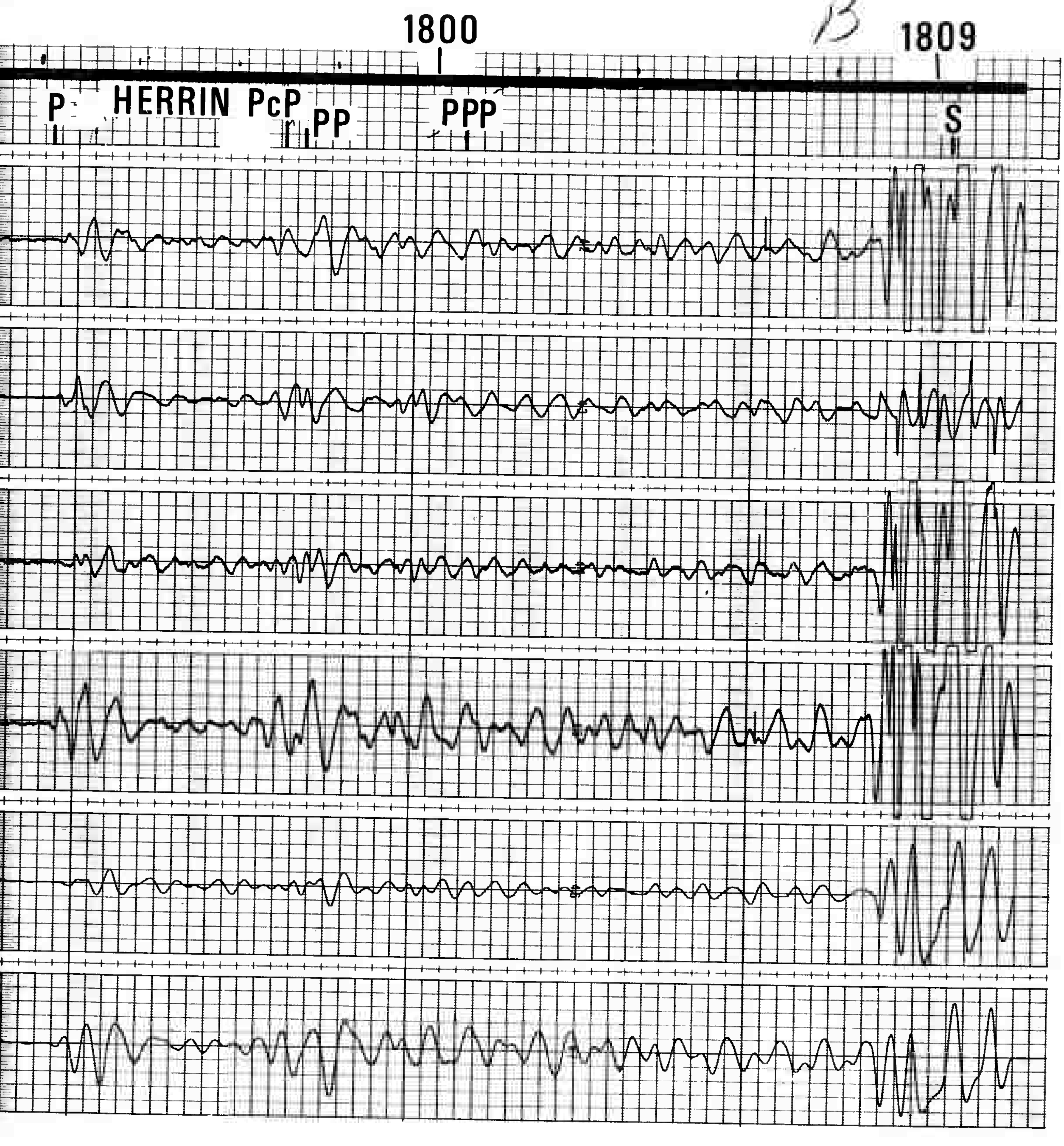
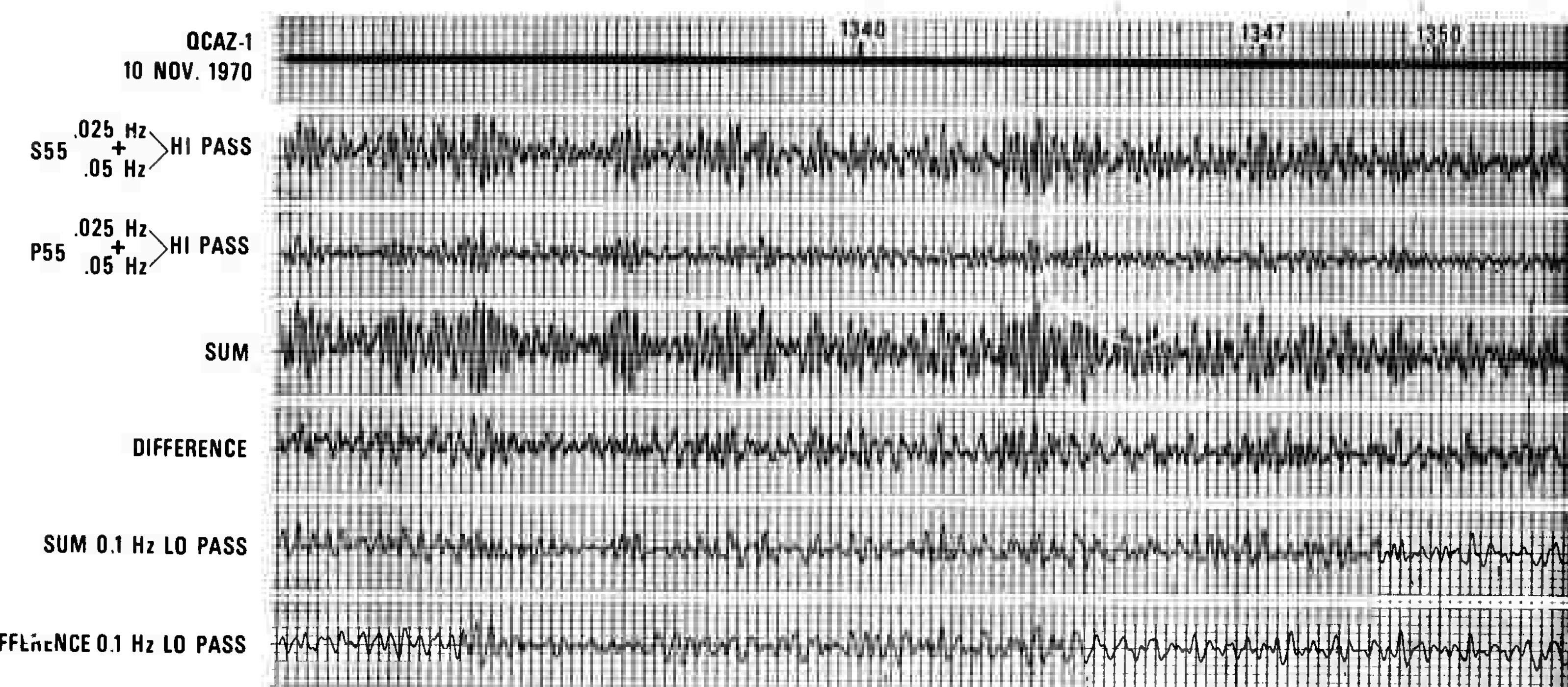


Figure 3. Long period P-wave signal enhancement Sea of Okhotsk earthquake (48).

A


QCAZ-1
10 NOV. 1970
1340
1347
1350
S55 .025 Hz + .05 Hz HI PASS
P55 .025 Hz + .05 Hz HI PASS
SUM
DIFFERENCE
SUM 0.1 Hz LO PASS
FFERENCE 0.1 Hz LO PASS

B

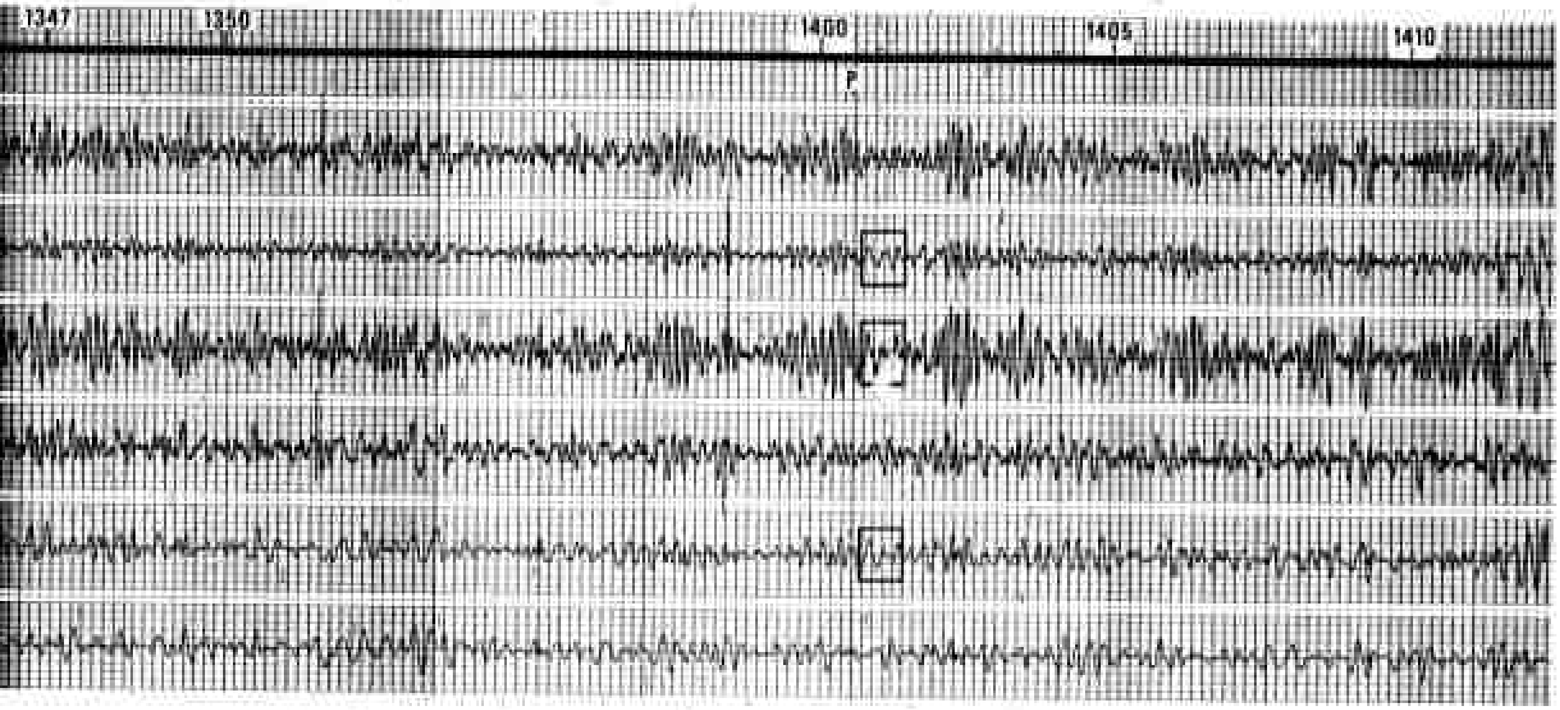
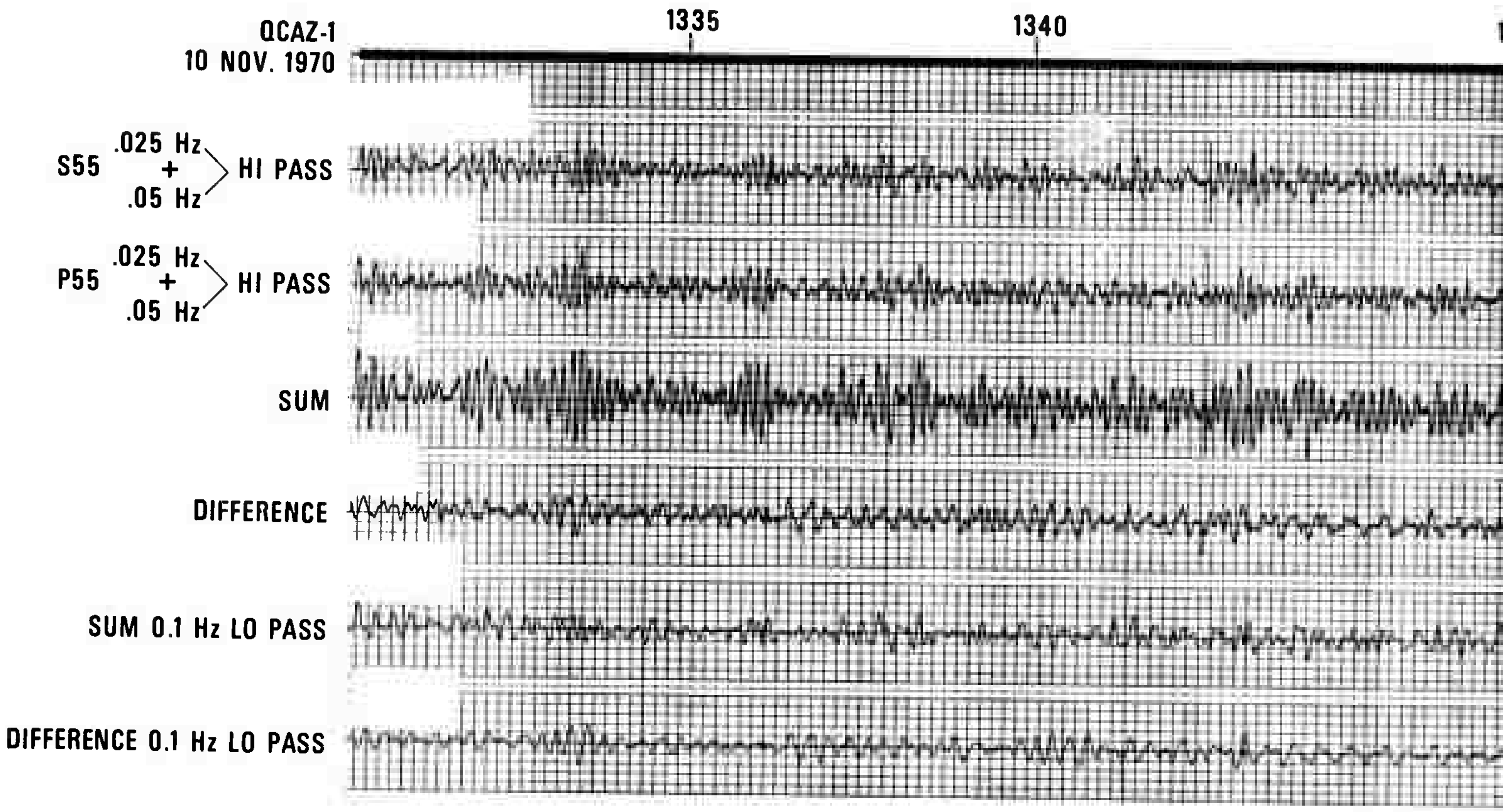


Figure 4. Long period P-wave signal enhancement Kermadec Islands earthquake (37).

A


QCAZ-1
10 NOV. 1970
1335
1340
S55 .025 Hz + .05 Hz HI PASS
P55 .025 Hz + .05 Hz HI PASS
SUM
DIFFERENCE
SUM 0.1 Hz LO PASS
DIFFERENCE 0.1 Hz LO PASS

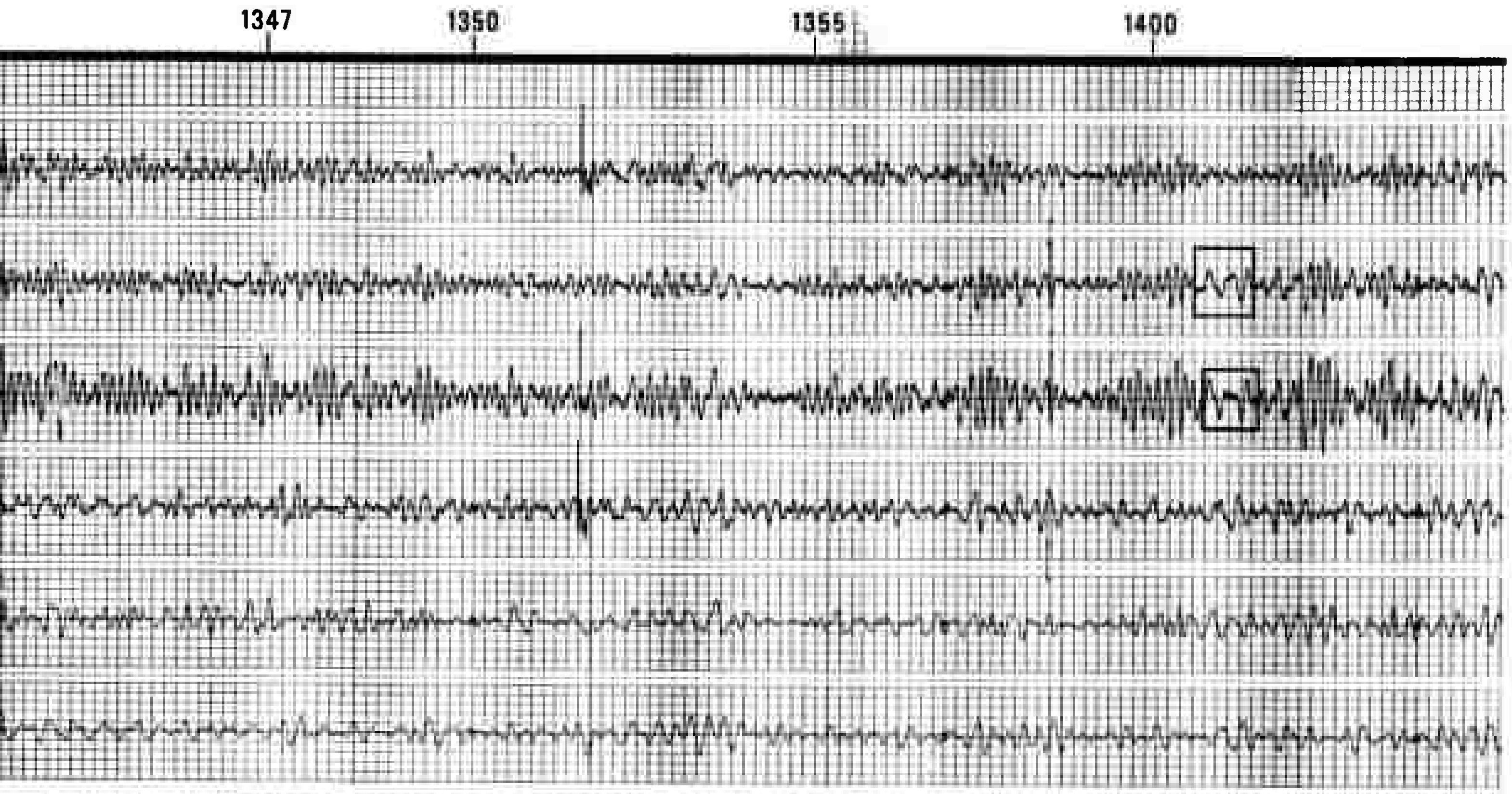
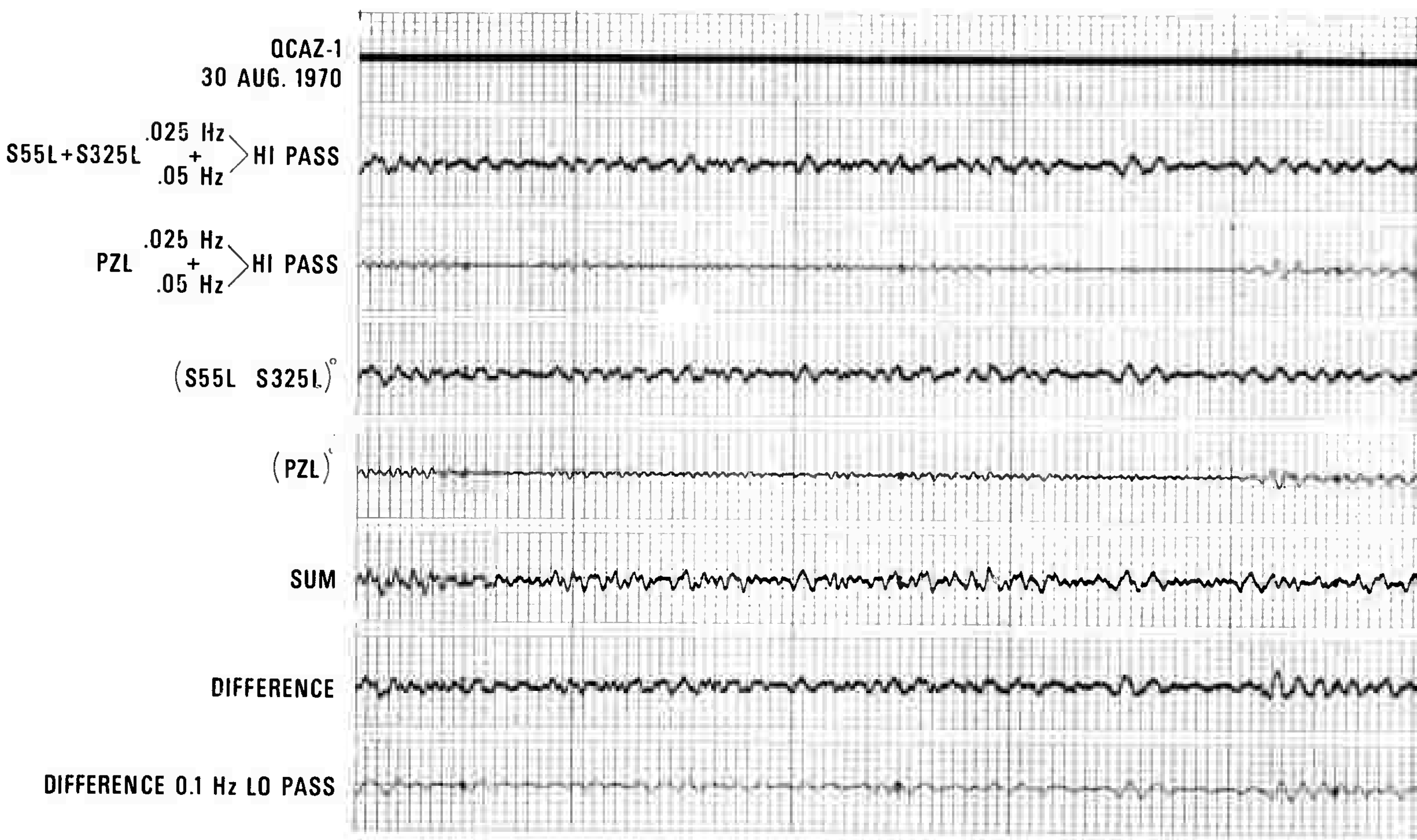


Figure 5. Cancellation of 7-second microseisms Kermadec Islands earthquake (37).

A


QCAZ-1
30 AUG. 1970
S55L+S325L .025 Hz + .05 Hz HI PASS
PZL .025 Hz + .05 Hz HI PASS
(S55L S325L)°
(PZL)°
SUM
DIFFERENCE
DIFFERENCE 0.1 Hz LO PASS

B

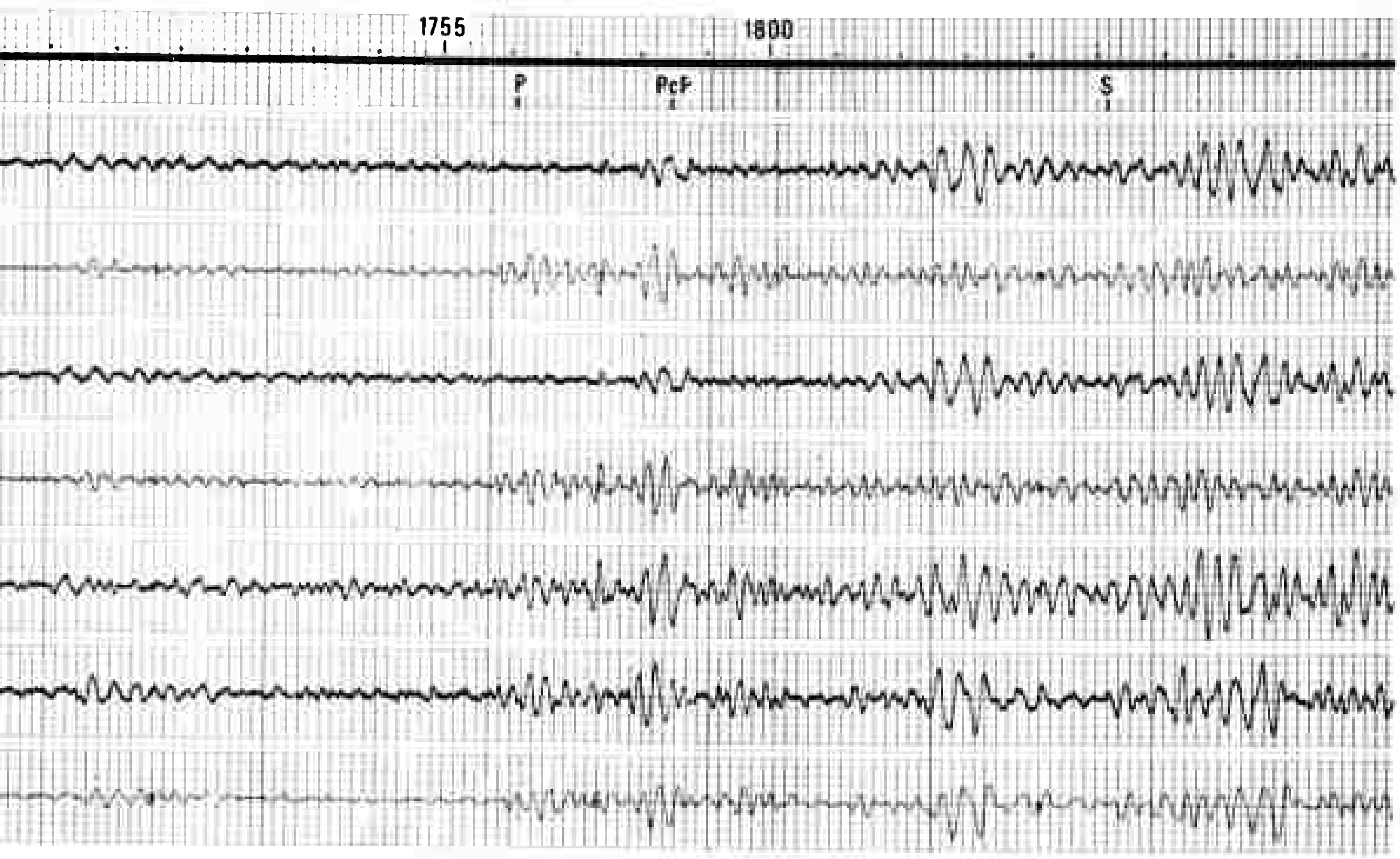
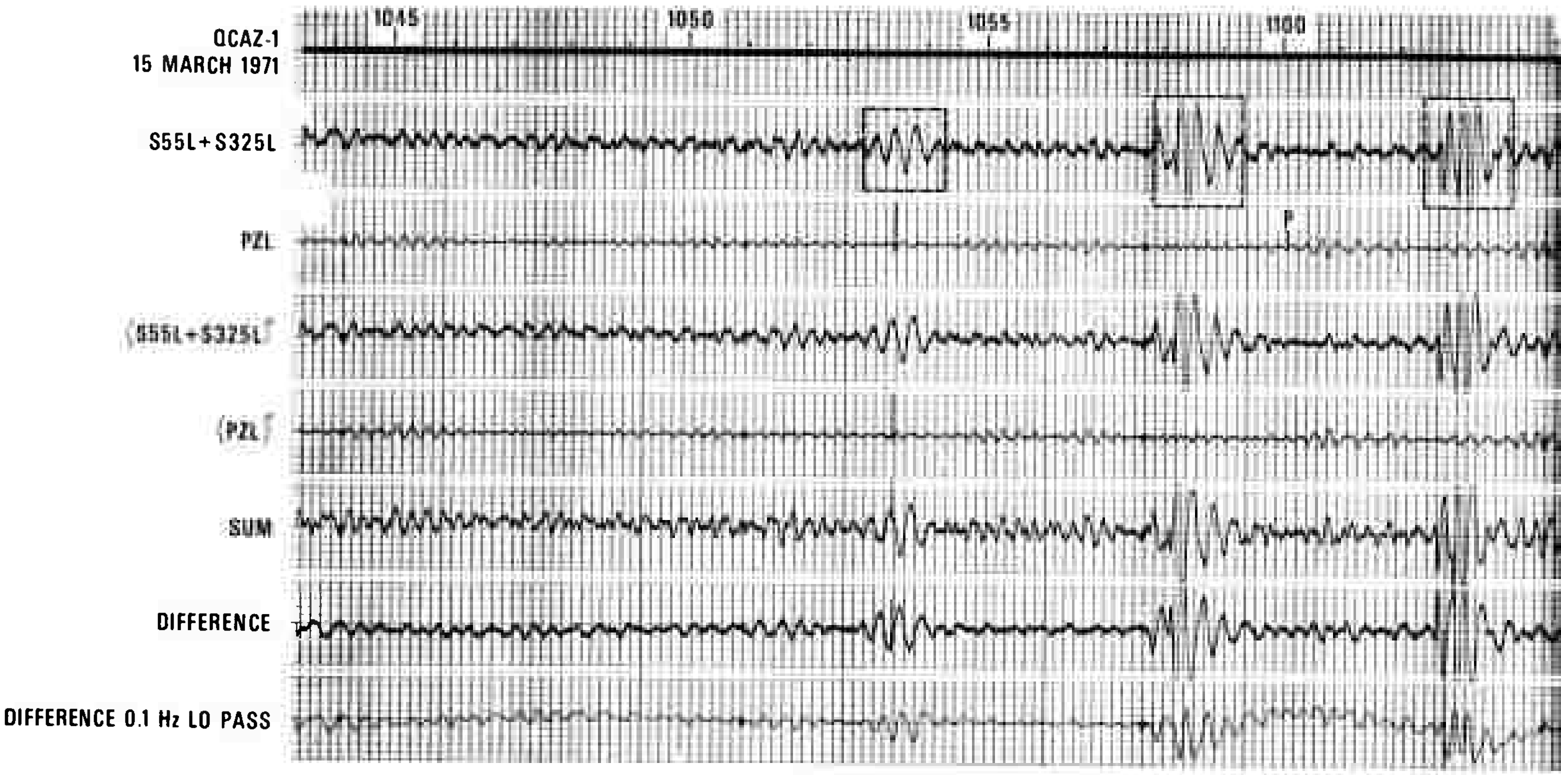


Figure 6. 30 August 1970 Sea of Okhotsk earthquake (48) on vertical pendulum and sum of horizontal strain seismographs.

A


QCAZ-1
15 MARCH 1971
S55L+S325L
PZL
(S55L+S325L)²
(PZL)²
SUM
DIFFERENCE
DIFFERENCE 0.1 Hz LO PASS
1045
1050
1055
1100
P

Figure

B

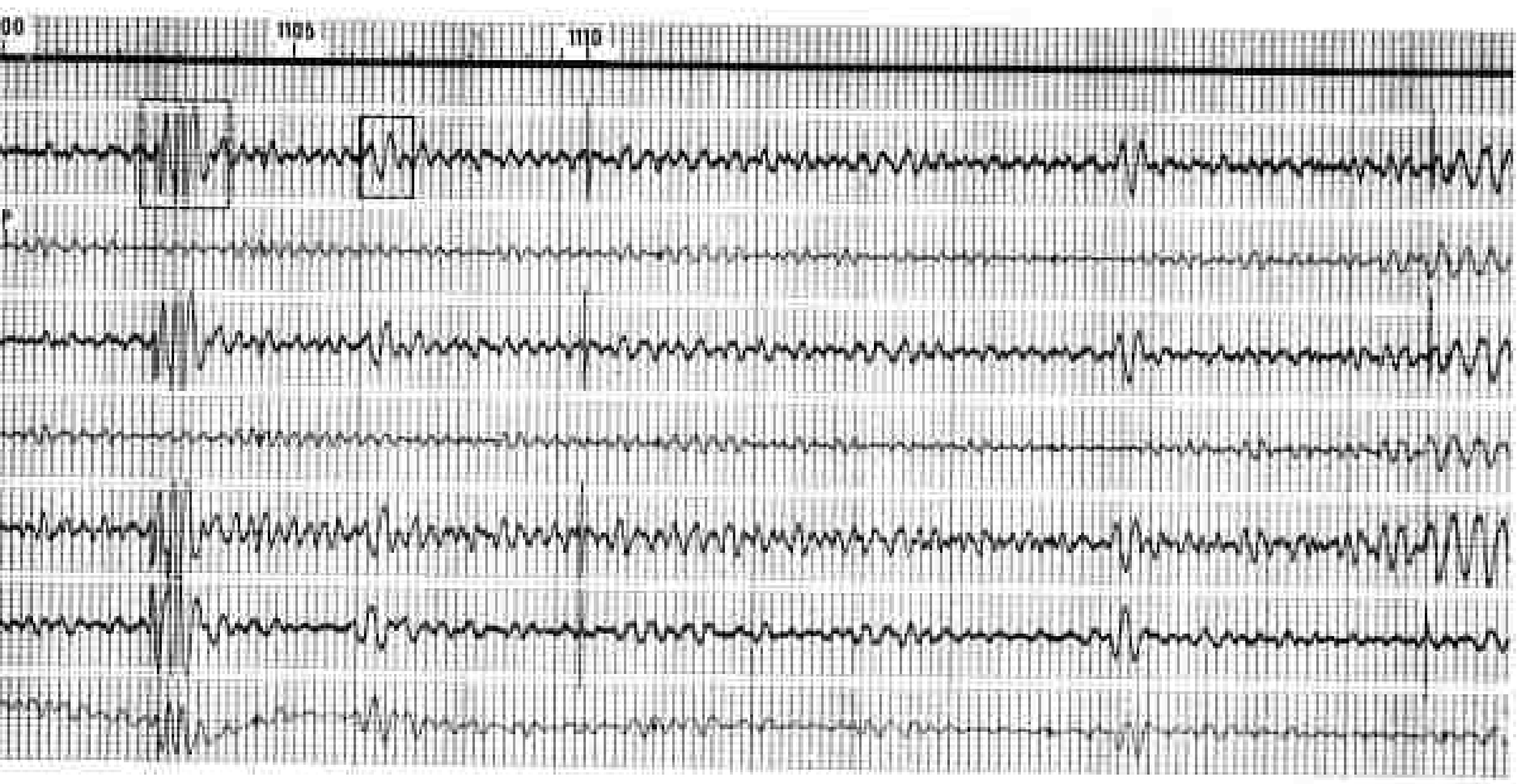
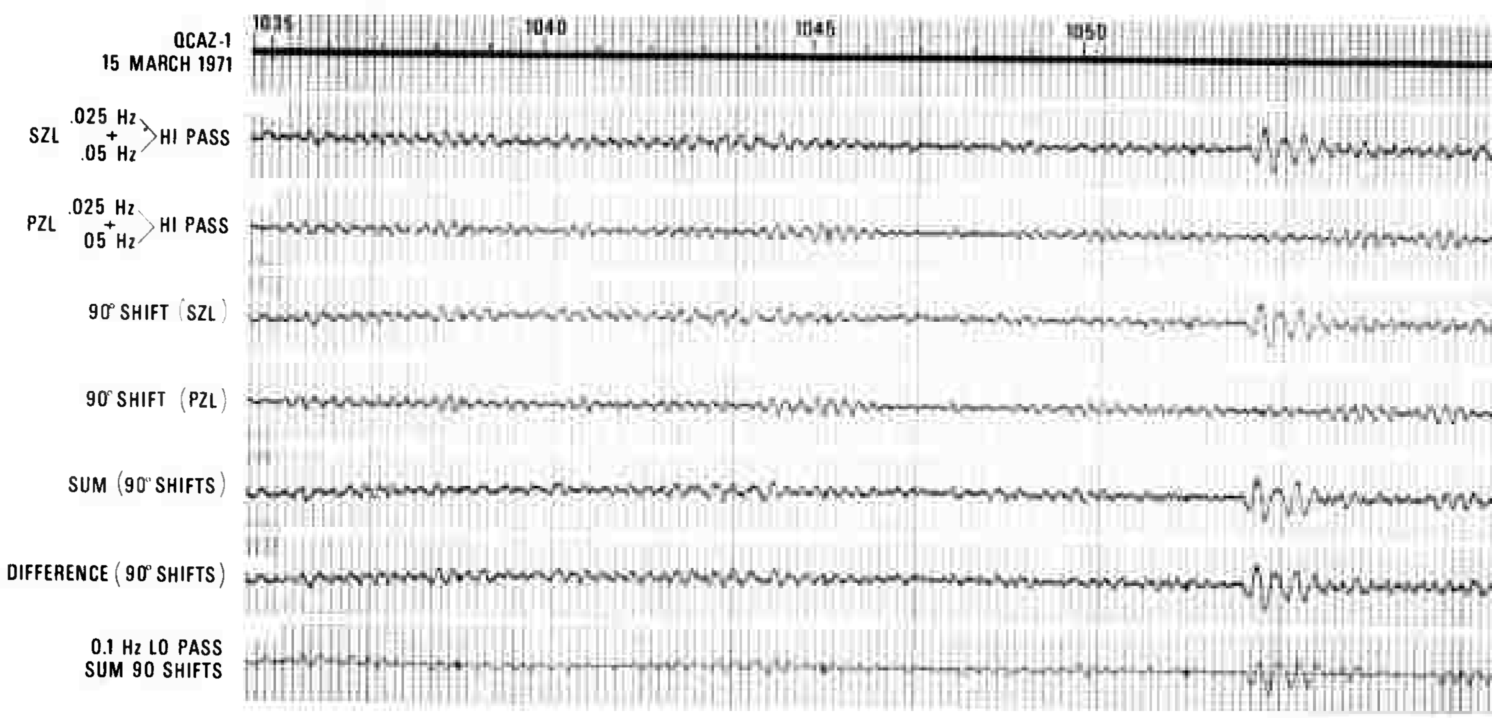


Figure 7. 16-Second microseism cancellation Tonga Islands earthquake (8).

A


QCAZ-1
15 MARCH 1971
1035
1040
1045
1050
SZL .025 Hz + .05 Hz HI PASS
PZL .025 Hz + .05 Hz HI PASS
90° SHIFT (SZL)
90° SHIFT (PZL)
SUM (90° SHIFTS)
DIFFERENCE (90° SHIFTS)
0.1 Hz LO PASS
SUM 90 SHIFTS

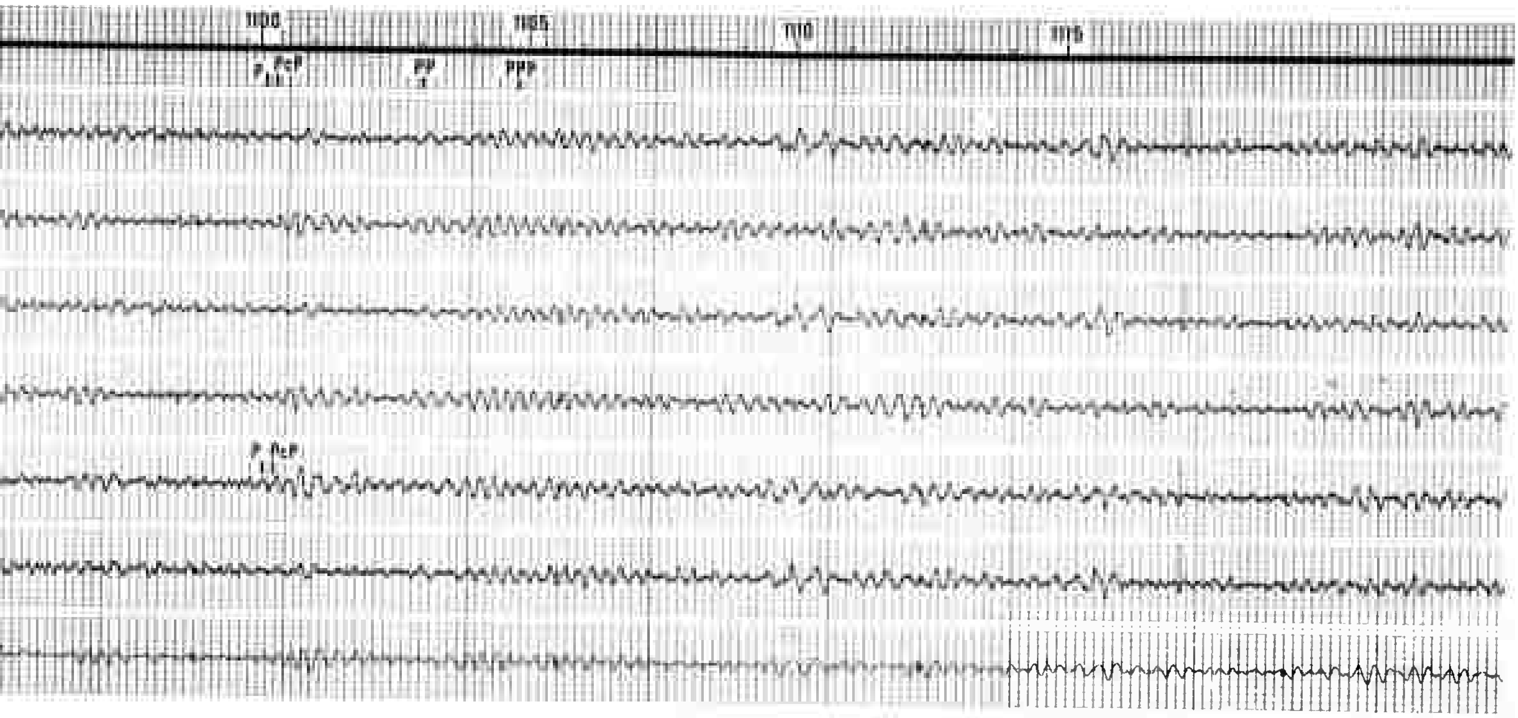
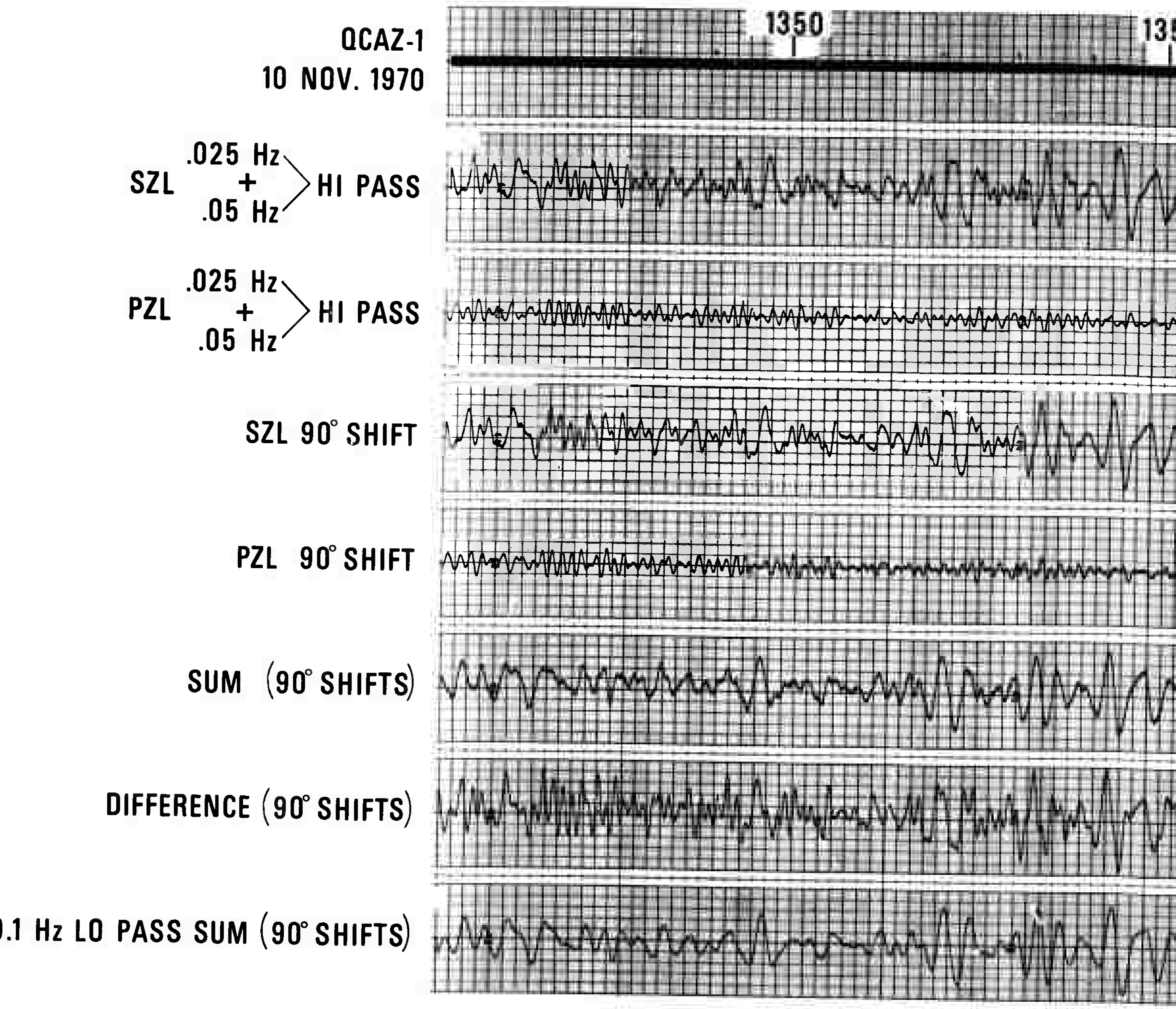


Figure 8. Vertical strain/vertical pendulum combination Tonga Islands earthquake (8).

A



Figur
earth

B

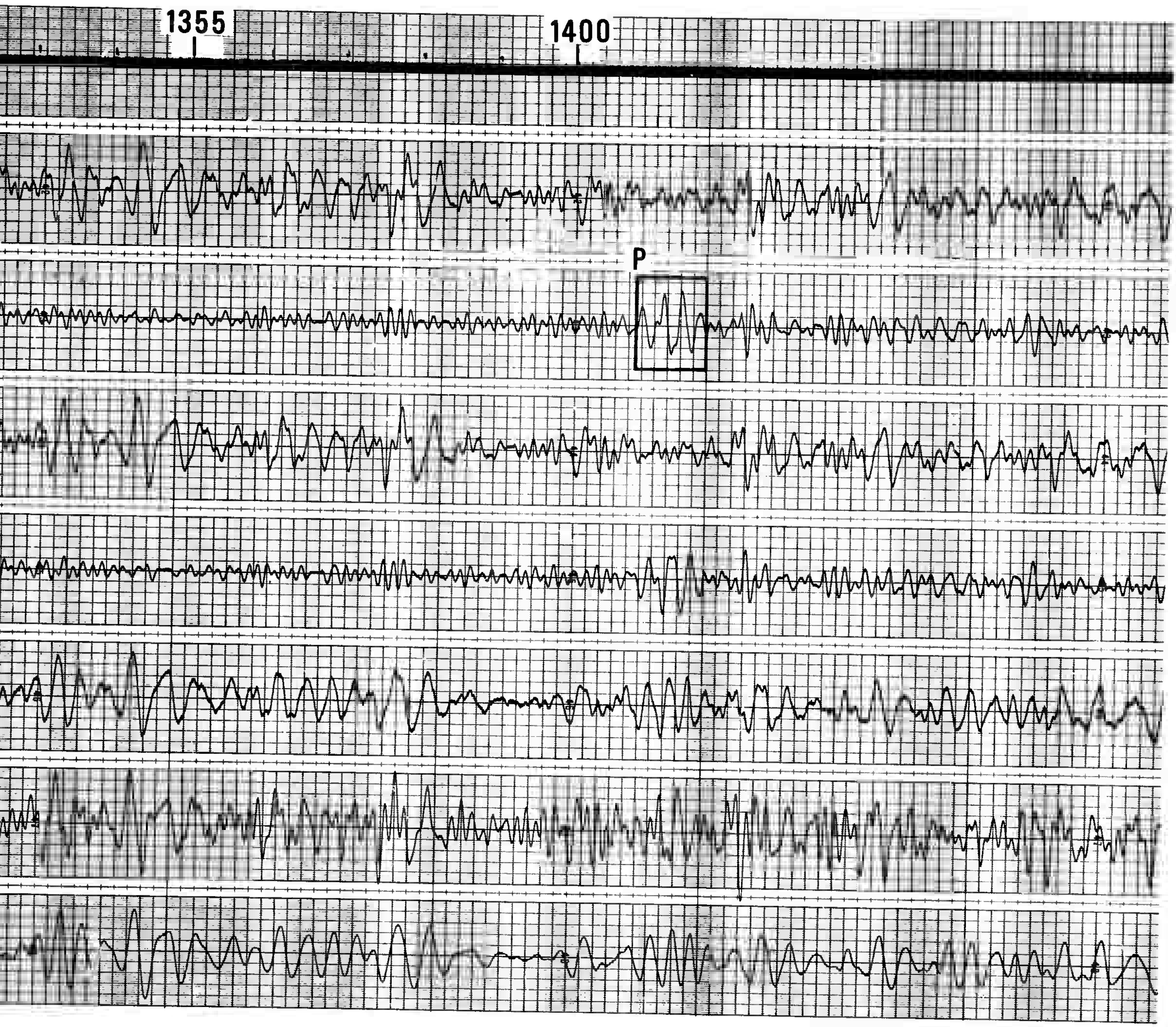
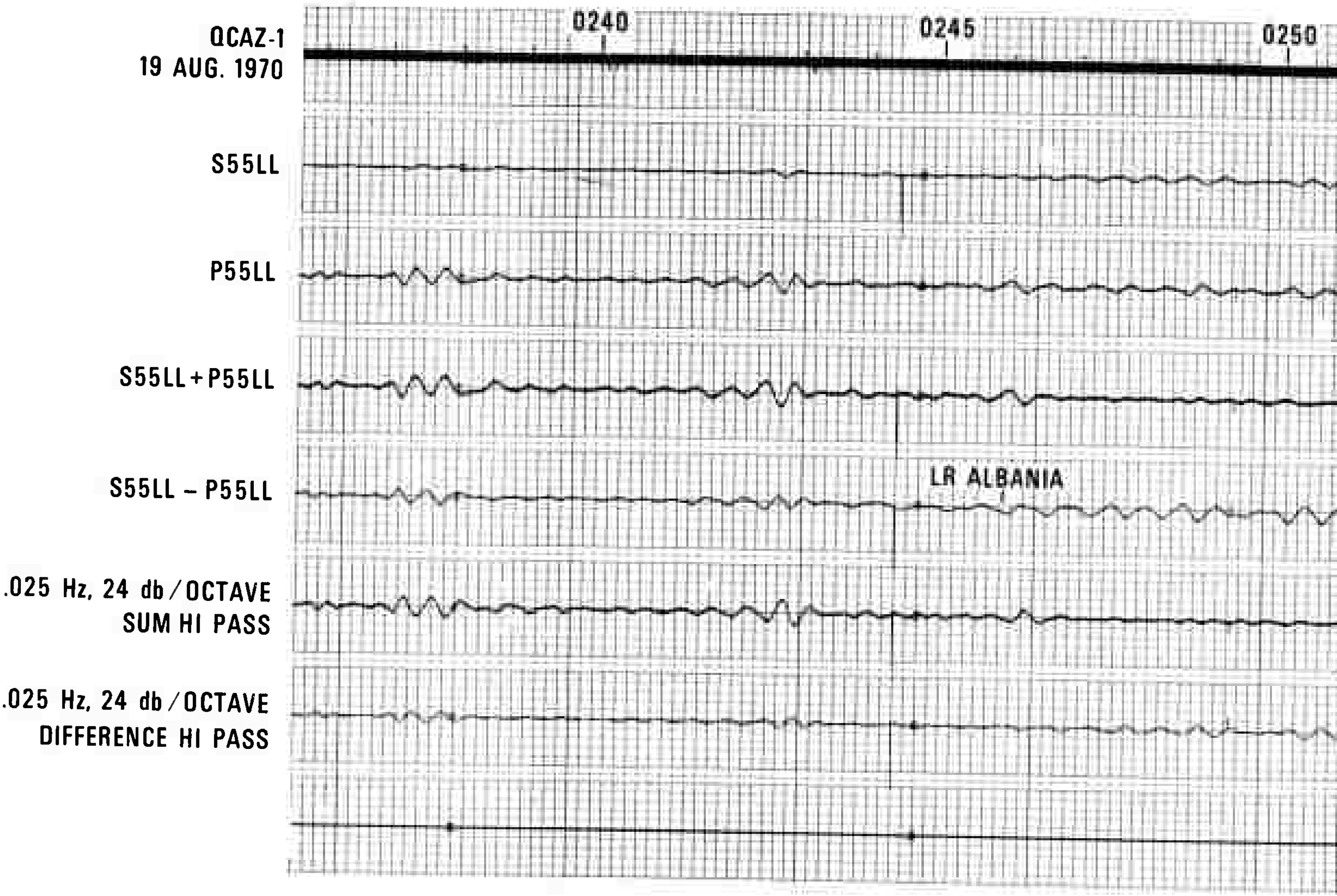


Figure 9. Vertical strain/vertical pendulum combination Kermadec Islands earthquake (37).

A


QCAZ-1
19 AUG. 1970
0240
0245
0250
S55LL
P55LL
S55LL+P55LL
S55LL – P55LL
LR ALBANIA
.025 Hz, 24 db/OCTAVE
SUM HI PASS
.025 Hz, 24 db/OCTAVE
DIFFERENCE HI PASS

B

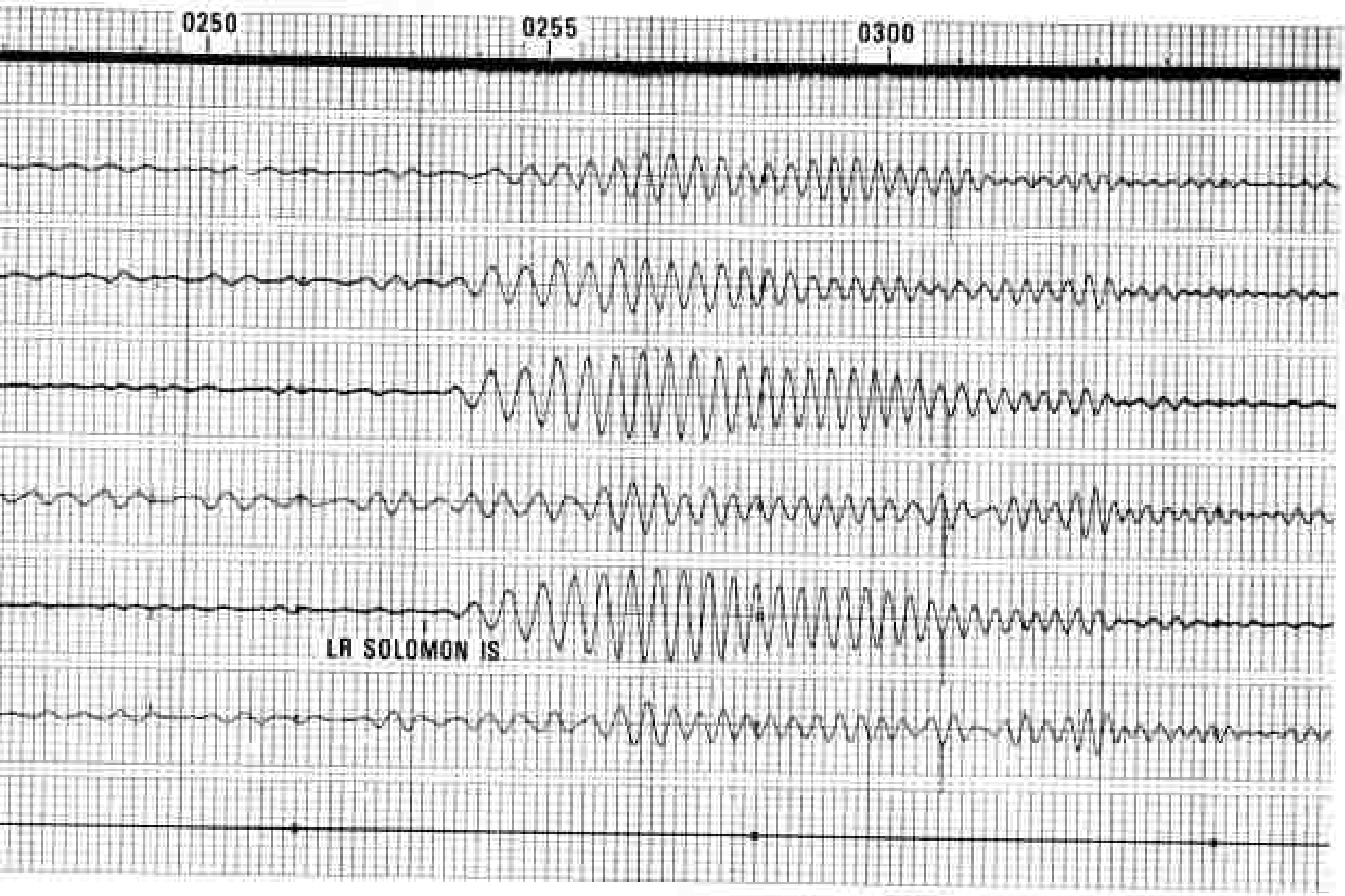


Figure 10. Simultaneously occurring Rayleigh wave signals 19 August 1970, Albania earthquake (10) and Solomon Islands earthquake (9).

APPENDIX I

Earthquake	m_b	Date	Location	Computed P-Arrival	Δ	Rayleigh Signal Back Azimuth P-P	Rejection rms.
1	4.7	10 Dec 70	Peru	10 07 33.7	47.3	31.5 db	27.0 db
2	4.7	10 Dec 70	Peru	9 27 22.2	47.0	33.0	36.9
3	5.4	10 Dec 70	Peru	11 46 15	47.1	38.4	36.9
4	5.5	10 Dec 70	Andreanof (Fox Islands)	10 23 24.9	45.5	37.5	36.1
5	4.7	19 Aug 70	Honshu	03 16 38.3		14.8	
6	5.1	11 Aug 70	New Hebrides	10 22 31	90.9	+	
9	5.7	19 Aug 70	Solomons	02 24 22.6	93.1		
10	5.2	19 Aug 70	Albania	02 15 08.1	93.6	13.4	18.1
11	6.2	11 Aug 70	New Hebrides	10 35 23.1	90.9	+	
13	4.7L	12 Mar 71	Oexaca, Mexico	~ 05 31	~25°	38.4	39.8
14	5.1L	12 Mar 71	Honshu	~ 03 12	~85°	22.3	16.9
15	4.5	06 Nov 70	Iceland	07 25 54.6	60.3°	17.5	17.6
16	4.7	01 Nov 70	Azores	00 28 38.8	63.2	8.2	10.6
	4.9			00 36 12.5	63.5	7.2	11.4
17	5.4	02 Nov 70	Fiji	10 25 34.9	78.3	10.3	12.6
18	5.1	05 Nov 70	N. Atlantic Ridge	20 46 20.9	60.5	12.0 db	8.0 db
19	5.8	01 Nov 70	Sandwich Island	13 32 53.2	115.7	9.2 db	10.6 db
20	5.6	03 Nov 70	Central Alaska	02 37 25.9	38.2	9.8 db	10.2 db
21	5.6	05 Nov 70	South of Panama	13 19 06.4	37.5	13.2 db	10.6 db
22	5.2	15 Mar 71	Tonga	~11 00 29	~81°	13.3 db	13.0 db
23	5.1	13 Mar 71	Honsha	~03 11 51		37.5 db	37.3 db
24	4.8	09 Mar 71	Panama	~13 25 30	~40°	21.2 db	18.6 db
25	5.4	06 Mar 71	Chili-Bolivia	~22 24 24	~68°	17.5 db	17.7 db
26	4.9	11 Aug 70	New Hebrides	16 29 21.8	90.6	22.0 db	18.6 db
26	5.5	19 Sep 70	Chili	06 49 16.9	76.1	9.9 db	Not Run
27	5.1	07 Nov 70	Kermader	07 58 5.3	93.2	8.6 db	4.8 db
28	4.9	09 Dec 70	Loyalty Island	~11 59 20	~90°	14.0 db	Not Run
29	5.3	10 Dec 70	Fox Islands	~14 56 30	~45°	15.6 db	Not Run
30	4.7	14 Dec 70	Ecuador	~15 37 45	~44.5°	19.6 db	Not Run
31	4.5	08 Nov 70	Guatemala	11 55 13.7	27.3°	13.4 db	12.0 db
32	4.7	12 Dec 70	Tunisin	~07 22 25	~90°	9.1 db	Not Run
33	5.5	12 Dec 70	Fiji	~01 22 20	~85°	12.6 db	Not Run
34	4.5	06 Nov 70	Iceland	07 25 54.6	60.3°	11.4 db	Not Run
35	4.3	06 Nov 70	Iceland	11 35 30.6	60.1°	14.8 db	Not Run
36	4.5	10 Nov 70	Panama Costa Rica	10 46 39.0	37.0°	19.2 db	20.8 db
37	5.4	10 Nov 70	Kermadec	14 00 33.0	90.2°	35.9 db	20.0
38	5.6	13 Nov 70	Northern Chili	00 19 57.0	67.8	11.4 db	8.3 db
39	5.2	13 Nov 70	Kermadec	02 24 25.3	90.7	13.7 db	18.8 db
40	5.0	14 Nov 70	South of Panama	04 49 47.2	38.0	34.8 db	32.6 db
41	5.5	14 Nov 70	South of Mariana Island	05 04 54.3	95.4	35.1	32.6 db
42	6.0	28 Nov 70	Northern Chili	11 19 34.5	67.0	14.9	17.9 db
43	5.9	28 Nov 70	Northern Chili	14 56 23.3	66.9	18.6	12.9
44	5.0	30 Aug 70	Andreanof	00 25 35.0	51.6	9.6	2.5
45	5.2	30 Aug 70	Kamchatka	00 49 11.5	63.9	Clipped	
46	5.0	30 Aug 70	New Ireland	00 42 26.9	96.8	16.0	15.6
47	5.3	30 Aug 70	Somoa	00 55 44.1	76.0	20.8	25.1
48	6.6	30 Aug 70	Sea of Okhotsk	17 56 07.6	68.3	Clipped	